

Development and Optimization of Modular Bioswale Systems for Enhanced Urban Stormwater Management in Davao City: A Systematic Literature Review

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Abstract. Urban areas in the Philippines, including Davao City, experience increased stormwater runoff and flooding due to rapid urbanization and climate change. Bioswales, which utilize vegetation and engineered soil, mitigate these issues by capturing runoff, enhancing infiltration, and filtering pollutants. Their modular design allows for scalability and easy maintenance, making them a promising solution for urban drainage. However, localized studies are necessary to assess their effectiveness under Philippine conditions. This study aims to develop a small-scale modular bioswale system, analyze existing drainage systems, create a modular design framework, and evaluate bioswale effectiveness through simulations and field tests. The research aligns with UN SDGs 6, 11, and 13. A systematic review using the PRISMA framework identified 16 relevant studies. Results showed that bioswales reduced surface runoff by up to 99.4%, runoff volumes by 15–82%, and achieved full infiltration in 37 of 39 storm events. Additionally, they lowered nitrogen loading by 30%, with rainfall intensity, site selection, soil composition, and vegetation significantly influencing performance. In conclusion, bioswales represent a sustainable urban stormwater management solution when supported by strategic design and regular maintenance.

1 Introduction

Urban areas in the Philippines are increasingly facing the challenges posed by rapid urbanization, climate change, population growth, and deforestation. The rapid growth of impermeable surfaces—such as roads, buildings, parking lots, and other infrastructure—has led to heightened stormwater runoff due to the lack of soil infiltration capacity [1]. Davao City, which is one of the fastest-growing cities in the country, is no exception to these challenges. With a growing population of over 1.77 million as of 2023, the city has undergone significant urban expansion, which has contributed to the loss of green spaces and natural

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drainage systems, as well as insufficient drainage systems [2,3]. As a result, this exacerbates flooding, water pollution, and increased vulnerability to climate-related events. These issues highlight the need for effective innovative solutions that not only manage stormwater effectively but also enhance sustainability and urban resilience against flooding and pollution.

Bioswales have the potential to address these issues by utilizing natural processes to manage stormwater. These are designed with dual-layered structures that seamlessly integrate surface vegetation and engineered soil zones. They operate like sponges, where the overland vegetation captures and slows down runoff, while the underlying soil zone—composed of porous media—facilitates infiltration and temporary storage. Gradually, the excess water is released into drainage systems or nearby water bodies, effectively mitigating flooding risks while filtering out pollutants [4]. The modular design of bioswales offers flexibility to scale them up or down to fit the available space of a site, whether for a large urban development or a smaller residential area. This adaptability allows the system to be tailored to the site's specific water management requirements and topography [5]. Furthermore, the modular approach simplifies maintenance by enabling individual sections to be repaired or replaced without disrupting the entire system. Given Davao City's extensive coverage of non-porous surfaces, this flexibility makes bioswales an ideal solution for managing urban stormwater effectively.

Most existing studies emphasize the general vulnerability of communities to flooding and highlight the critical need for enhanced disaster risk management strategies [6, 7]. However, there is a notable absence of research focusing on tailored, scalable, and site-specific interventions in the local context that align with the unique environmental, urban, and socio-economic conditions of cities like Davao City [8]. Although bioswales have been implemented in other countries, their viability in the Philippines remains uncertain due to local challenges like high humidity, extreme rainfall, and typhoon exposure. Modular bioswales, in particular, have shown promise in urban landscapes globally but remain underexplored in the Philippine context. This gap raises concerns about their applicability in a setting where inadequate drainage infrastructure and rapid urbanization exacerbate flood risks.

Without localized studies that consider these region-specific factors, the effectiveness of bioswales as a sustainable stormwater management solution in the Philippines remains largely theoretical. The absence of detailed studies evaluating the feasibility, design, and integration of modular bioswales in urban areas like Davao City limits the actionable knowledge needed to address localized flooding and water quality issues.

This study seeks to address this gap by (1) developing and prototyping a small-scale modular bioswale system for localized urban runoff management, (2) analyzing the current drainage systems in selected areas of the city, (3) creating a modular design framework tailored to the specific needs and conditions of the city, and (4) conducting simulations and small-scale field tests to assess the effectiveness of the proposed bioswale design in terms of reduction of flood risks, as well as enhanced stormwater management and water quality.

2 Methodology

Figure 1 below shows the entire methodological process of this review. This study adopted the guidelines presented in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Framework to execute a systematic literature review regarding the implementation of modular bioswales to address and mitigate the severity of flooding consequences within the local area of Davao City. The selected studies are examined based on established eligibility criteria indicating the grounds for inclusion and exclusion. The review's findings will serve as basis for interpretations, informed recommendations, and a substantiated conclusion to support flood mitigation efforts.

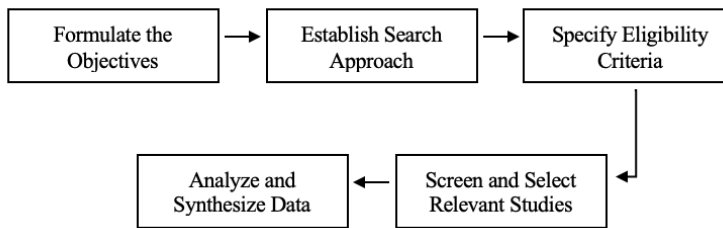


Fig. 1. Methodology Outline

2.1 Formulation of the Problem

Despite ongoing endeavors to mitigate flooding in Davao City, its impact on residents remains a problem, with existing measures yet to significantly reduce flood risks. While disaster risk reduction strategies help lessen its severity, alerting residents and evacuating areas only provide superficial measures that do not alleviate communities from the aftermath, including property damage, economic losses, health risks, displacement, and disruptions to daily life. Introducing a promising approach, the integration of modular bioswales in strategic urban spaces within Davao City, potentially offers a sustainable countermeasure to this persistent concern. Hence, the following questions are formulated to explore the critical aspects and technical considerations of modular bioswales, their dynamics in flood reduction, and documented outcomes that may contribute to a comprehensive analysis of their integration in the local areas of Davao City:

1. What are the key design considerations that influence the efficiency, longevity, and overall performance of modular bioswales?
2. What are the optimal soil compositions and vegetation types used in modular bioswales tailored to local conditions?
3. What are the measurable impacts of modular bioswales in terms of:
 - a. Stormwater infiltration
 - b. Filtering pollutants
 - c. Surface runoff reduction
 - d. Long-term performance

2.2 Data Sources and Strategy

This study establishes a search strategy for identifying relevant literature on the necessary specifications and conditions needed to develop a modular bioswale system in Davao City. The strategy includes gathering information from online academic databases such as ScienceDirect, MDPI, MATEC Web of Conferences, PJOES, and Forestist to ensure

reliability and comprehensiveness. These databases encompass journal articles, research papers, and studies that focus on tackling the technical aspects of modular bioswales, particularly those that have been implemented in urban areas with similar environmental conditions as Davao City. Furthermore, utilizing selected keywords, namely bioswales, flooding, stormwater management, and flood mitigation will help narrow down the search results and provide more relevant information for the development of the modular bioswale system in the local context.

2.3 Eligibility Criteria

Table I below presents the Eligibility Criteria implemented in the selection process of related literature. The screened data will concentrate on peer-reviewed journal articles that examine flood mitigation through bioswale implementation. Studies should also adhere to the 10-year recency standard (2015-2025) and be fully accessible, with well-supported findings. Otherwise, they will be excluded. English-language publications are prioritized, while non-English studies without official translations are omitted. Likewise, qualitative studies, editorials, and research with unaligned methodologies are excluded, along with publications from predatory journals.

Table 1. Inclusion and Exclusion Criteria

Include	Exclude
Peer-reviewed journal articles	Studies with misaligned methodologies
Articles from 2015 to 2025	Studies beyond the 10-year recency standard
English-language publications	Non-English publications without official translation
Full-text accessible articles	Restricted studies
Articles with substantiated findings	Studies lacking clear methodology or results
Year	Qualitative studies, editorials, or non-scientific articles
	Studies from predatory journals

2.4 Analysis of Relevant Studies

Table 2 presents key studies relevant to this systematic literature review, detailing their corresponding authors, methodologies, contributions, and findings that may provide valuable insights for this research.

Table 2. Summary Of the Selected Studies Based on The Criteria

Study	Focus/Method	Key Contribution	Main Finding
Abdurrasheed et al. (2018)	Review of subsurface drainage modules in BIOECODS	Identified design and maintenance challenges in drainage modules	Effective for stormwater control, but performance is limited by clogging, maintenance, and climate
Brankovic et al. (2019)	Review of bioswale practices and site suitability in Serbia	Highlighted urban locations suitable for bioswales	Bioswales are cost-effective and appropriate for streets,

			parking lots, and waterfront zones
Chen et al. (2023)	Field-scale and simulated rainfall assessment in Hong Kong	Evaluated bioswale efficiency under climate and design constraints	Performed well in minor to moderate rainfall, but less effectively in heavy rainfall
De Macedo et al. (2022)	Simulation-based modular bioretention design	Integrated urbanization and climate change into design analysis	Runoff coefficient and precipitation strongly affect performance; modular systems remain robust
Ekka et al. (2020)	Empirical monitoring of runoff water quality	Assessed pollutant removal in bioswales	Reduced nutrients and sediments, improving stormwater quality
Finotti et al. (2023)	Monitoring infiltration swale in tropical coastal setting	Examined effects of seasonal rainfall and sea-level influence	Delayed peak flow, though runoff reduction varied across seasons
Li et al. (2020)	Integrated hydrologic and hydraulic modeling	Proposed framework for evaluating roadside bioretention	Runoff reduction depends on inlet design, storage, and infiltration
Li et al. (2015)	Column experiments and regression analysis	Identified optimal bioswale media composition	Water reduction improved with lower inflow; sand performed best
Lu et al. (2024)	SWMM and ensemble modeling	Examined bioswales as climate adaptation measures	Effective in reducing runoff, especially at early rainfall peaks; 4% catchment coverage was needed
Miner et al. (2016)	Long-term field monitoring before and after installation	Provided long-term evidence on pollutant reduction	Wet bioswales favored dissolved pollutant removal; dry bioswales were better for TSS reduction
Mobron (2019)	Field monitoring and Hydrus modeling under polder conditions	Explained influence of soil, vegetation, and storms on hydraulic behavior	Reduced peak flow during extreme storms, but volume reduction was limited by high groundwater
Purvis et al. (2019)	12-month field monitoring	Supplied real-world data on bioswale hydrologic benefits	Managed most monitored rain events successfully, including storms larger than design conditions
Regier & McDonald (2022)	Monitoring runoff and water quality in urban farm bioswales	Evaluated hydrologic and pollutant-control performance	Reduced runoff and peak flow, with strong TP reduction but mixed TN and TSS results
Sen & Sat (2024)	Systematic literature review	Synthesized design, material, and maintenance factors	Bioswales are effective when properly designed, but more real-world studies are needed
Xiao et al. (2017)	Field evaluation of two urban bioswales	Provided empirical evidence on runoff control	Reduced runoff and improved water quality; performance depended on soil, vegetation, and maintenance
Zhou et al. (2021)	Simplified mathematical modeling	Developed predictive tool for bioswale efficiency	Performance depends on area ratio, rainfall, and maintenance; sediment reduces effectiveness over time

3 Results and Discussions

The selection process for the literature review is illustrated in Figure 2. The systematic review began with the identification of 66 articles. Five duplicates were then removed, which reduced the number of records to 61. However, 12 of these were excluded based on their titles and abstracts as they did not meet the predefined search criteria. This left 49 articles, 14 of which were not accessible. As a result, only 35 articles were eligible for full-text evaluation. However, 18 failed to meet the inclusion criteria: four were non-English articles, nine were irrelevant to the study's focus, five were outside the 10-year recency standard, and one was from a predatory website. Ultimately, 16 studies were included in the final review.

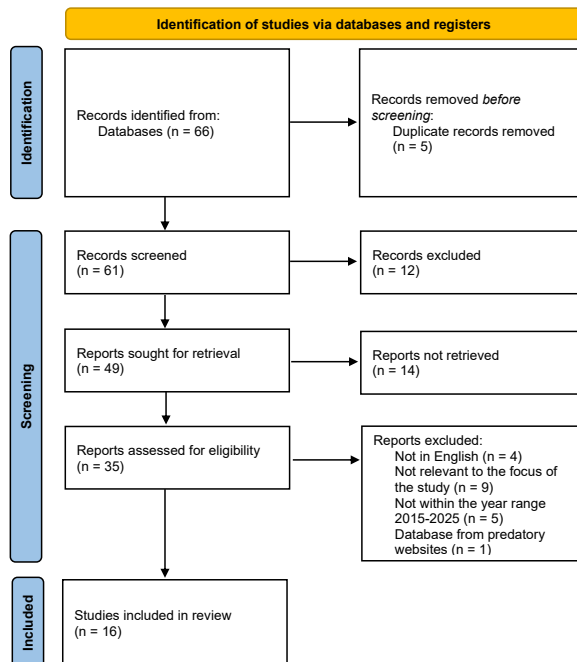


Fig. 2. PRISMA Framework

3.1 Design Parameters for Maximizing Bioswale Efficiency

The ability of modular bioswales to effectively reduce stormwater runoff depends on key design parameters that dictate their hydraulic efficiency, infiltration capacity, and long-term functionality. Upon assessing various studies, critical considerations include rainfall intensity and sea levels, site selection, modular bioswale sizing methods, and sediment buildup with maintenance requirements. These factors directly influence stormwater absorption rates, pollutant filtration efficiency, and overall system durability.

Environmental conditions, particularly rainfall intensity and sea levels, significantly impact bioswale performance. A study by [9] on a bioswale simulated in Hong Kong found that while it retained surface runoff effectively during minor and moderate rainfall events, intense rainfalls led to overflow due to limited storage capacity and insufficient filtration rates. Similarly, [10] linked bioswale efficiency to seasonal rainfall patterns and sea levels, showing that higher infiltration rates (57%) occurred during summer and spring when sea levels were lower, whereas extreme rainfall events combined with high sea levels resulted in overflow. In contrast, autumn and winter rains, being lower in volume and more evenly

distributed, led to more stable infiltration rates. These findings suggest that bioswales in coastal or flood-prone areas must account for fluctuating sea levels and seasonal variations to optimize stormwater management.

Given the influence of rainfall patterns, selecting appropriate bioswale locations is crucial to maximizing efficiency and mitigating overflow risks. According to [11], residential streets, parking lots, and waterfront zones offer optimal locations for modular bioswales. Residential streets benefit from bioswales integrated into roadside green spaces, where a recommended minimum width of 10 meters and a gentle slope ($\leq 5\%$) improve stormwater treatment, traffic calming, and pedestrian safety. Meanwhile, parking areas, both large and small, utilize bioswales to reduce runoff, mitigate heat island effects, and enhance urban aesthetics. Lastly, waterfront zones, particularly open green spaces along rivers and water bodies, serve as ideal bioswale sites for controlling flooding, restoring ecosystems, and improving urban landscapes.

To ensure long-term performance, proper sizing methods and storage capacities must address climate variability, urbanization, and system aging. [5] highlights that rainfall patterns, soil type, and runoff coefficients influence bioretention efficiency, with bioretention surface area positively correlating to runoff retention ($r = 0.48$) and peak flow attenuation ($r = 0.51$). Additionally, [12] emphasize that storage capacity is dictated by inlet design and inflow distribution, where catch basin efficiency varies (35–48%), and improper perforation spacing can lead to short-circuiting, reducing effectiveness. Optimizing these parameters through hydraulic analysis ensures that bioswales effectively manage stormwater over time.

Regardless of meticulous design planning, sediment buildup poses a challenge to modular bioswale efficiency by reducing infiltration capacity over time. [13] emphasize that accumulated sediments in the upper layers restrict water flow, diminishing overall effectiveness. Routine monitoring of permeability and clogging rates is necessary to sustain long-term performance. Effective maintenance strategies, such as periodic removal of accumulated sediments and vegetation management, can help restore infiltration efficiency and extend the bioswale's functional lifespan. Once all these considerations are applied, the modular bioswales may then adopt ideal soil compositions and vegetation selections that suit the potential locales for modular bioswale implementation.

3.2 Optimal Soil Compositions and Vegetation Selection

Bioswales are an effective green infrastructure solution for managing stormwater runoff, but their performance is highly dependent on soil composition and vegetation selection. Studies have highlighted the importance of soil media in determining infiltration capacity and pollutant removal efficiency. [14] conducted bioswale column experiments and found that sand was the most effective soil for water infiltration, improving rates by 45% compared to other soil types. Additionally, [5] emphasized that the sizing and composition of bioretention systems significantly influence their ability to handle urbanization and climate change impacts. Soil mixtures that include a balance of 60% to 70% sand, 20% to 30% loam, and 5% to 10% organic matter ensure both adequate infiltration and nutrient retention in bioswales.

Vegetation also plays a critical role in bioswale functionality by stabilizing the soil, improving infiltration rates, and enhancing pollutant removal. [15] demonstrated that bioswales with diverse plant species, specifically tall and stiff grass blades and non-clumping grasses with high density, with a coverage of 3,000 – 9,000 stems/m², effectively reduced nutrient and sediment levels in stormwater. [16] further distinguished the effectiveness of wet and dry bioswales, showing that wet bioswales perform better at removing dissolved pollutants, chloride and roadway metals, while dry bioswales are more effective for sediment filtration.

Soil composition directly influences vegetation growth in bioswales by affecting water infiltration, nutrient availability, and root development. As highlighted by [17], bioswales with well-drained soils had healthier vegetation, whereas another bioswale exhibited poor vegetation due to low soil permeability. However, while larger plants can enhance infiltration rates, they also increase the risk of clogging, emphasizing the need for careful selection of plant species and soil specifications based on bioswale design and local conditions.

3.3 Optimal Soil Compositions and Vegetation Selection

Bioswales have demonstrated significant effectiveness in managing stormwater by enhancing infiltration and reducing runoff volumes. According to [18], a bioswale successfully infiltrated a large storm event of 86.1 millimeters, highlighting its capacity to handle large volumes of water without overflow. Over the monitoring period, 37 out of 39 storm events were completely infiltrated. This indicates that bioswales can significantly reduce stormwater runoff. Furthermore, as documented by [15], their ability to lower peak runoff rates by 4% to 87% and runoff volumes by 15% to 82% makes them valuable in reducing localized flooding risks. These findings suggest that bioswales can mitigate urban flooding by decreasing the burden on traditional drainage systems. However, their effectiveness varies depending on site conditions and design characteristics.

Beyond managing runoff, bioswales also improve water quality by filtering pollutants from stormwater. Bioswales equipped with internal water storage zones can create anaerobic conditions that enhance nitrogen removal through denitrification [15]. This natural filtration process contributes to cleaner urban water systems and supports the role of bioswales as a sustainable stormwater management strategy.

Despite their advantages, the long-term performance of bioswales depends on proper maintenance and design. Hydrologic modeling has shown that bioswales can effectively reduce surface runoff, controlling 36% to 44% of runoff volume during storm events, depending on inlet design and inflow distribution [12]. With proper maintenance, bioswales retained their infiltration capabilities over time, showing minimal clogging and degradation [18]. However, [15] warned that neglecting maintenance can compromise their effectiveness and may lead to higher costs in the long run.

4 Conclusion

The review of systematic literature demonstrates that bioswales are an effective green infrastructure solution for managing stormwater, reducing runoff, and improving water quality. Their performance depends on key design factors, including sizing methods, site placement, and maintenance strategies. Environmental conditions such as rainfall intensity, sea level changes, and rapid urbanization also influence their efficiency, with high-intensity rainfall posing overflow risks if not properly accounted for in the design. Strategically placing bioswales in residential streets, parking lots, and waterfront areas enhances flood control and urban water management. However, inadequate design or lack of upkeep can reduce their effectiveness, leading to poor drainage performance and increased runoff, ultimately diminishing their ability to manage stormwater efficiently.

The composition of soil and vegetation is essential for maximizing bioswale efficiency. A well-balanced soil mix of sand, loam, and organic matter provides optimal infiltration and pollutant filtration, while vegetation stabilizes the soil, enhances water absorption, and aids in pollutant removal. Stiff grasses and diverse plant species help reduce nutrient and sediment levels, but larger plants, though beneficial for infiltration, may also contribute to clogging.

Therefore, selecting appropriate soil composition and plant species based on site-specific conditions is crucial for maintaining long-term functionality.

Overall, bioswales provide a sustainable and multifunctional approach to urban stormwater management. Their ability to mitigate flooding, enhance water quality, and seamlessly integrate into urban environments makes them a valuable component of resilient city planning. However, maximizing their benefits requires a comprehensive strategy that includes thoughtful design, appropriate soil and vegetation selection, and consistent maintenance. As cities continue to face challenges such as flooding, climate change, and rapid urbanization, well-designed bioswales offer a practical and environmentally friendly alternative to traditional drainage systems.

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